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Control System Design of an Ultra-Small Deep Space Probe

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Abstract

It's a grand opportunity to build new small deep space probe called Shinen2, developed by Kyushu Institute of Technology (KIT), in corporation with the different companies and institutions of engineering in Kagoshima University (Japan), NASA Johnson Space Center, was launched by the rocket H-IIA of Japan Aerospace Exploration Agency (JAXA) with Hayabusa 2, on December 3, 2014 in Tanegashima. This project involves Japanese students and foreigners, permitted a multi-cultural environment and an excellent tools for education. The students are in charge for the design, assembly, integration, tests of the space probe subsystems, and build-up of the existing ground stations facilities for tracking the telemetry data of Shinen2. It will enhance capacity building for the students, and scientific research for upcoming studies. The main approach to carry out the main mission of space probe. In parallel, to develop each subsystem of Shinen2: structure design, system bus architecture including the Communication Control Unit CCU, Power Control Unit PCU specifications, and new Particle Pixel Detector PPD for deep space radiation exploration. The development period for the space probe was only one year; it was extremely a short term. The mass budget and size were strictly limited while requiring a higher reliability. This paper describe a control system design for a small deep space probe which was developed to implement different missions and to satisfy the various requirements listed below.

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Keywords: Shinen2 project; deep space probe; system control unit; sensor radiation.

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1. Introduction

In few previous years, larger number of satellites were launched to the deep space as Hayabusa2, Despatch and Procyon [1], many universities and institutions around the world have now the capability to build small satellites and spacecrafts with different missions for the purpose of the space education and technology demonstration.

Shinen2 is the first ultra-small deep space probe, is described in Fig.1, was developed by Kyushu Institute of Technology in partnership with Kagoshima University (Japan) and Prairie View A&M University (U.S.A). The Space probe was launched by an H-IIA rocket in Tanegashima Space Center, on December 3rd, 2014, together with the asteroid probes listed before. Shinen2 has three main objectives as a space mission: the first mission of Shinen2 is to establish a mutual communication technology between the earth and a space probe near the lunar orbit and establishing a communication above 1 million km distance as full mission by many amateur radio stations, the second is the demonstration in deep space of a structure made of Carbon Fiber Reinforced Thermoplastic CFRTP material. The last mission, as payload for measuring radiation intensity using particle pixel detector to evaluate the distribution of the cosmic radiation [2].

The purpose of this paper is to describe the design of system control unit of Shinen2 space probe missions as well as providing an overview of the space probe might help developers in planning and developing satellites under 50kg.

The current paper describes different sections present the Shinen2 subsystems missions, orbit definition, satellite structure, the system bus architecture, power control specifications and communication control unit. The main approach is the measurement of space radiation environment between the cosmic radiation from the earth via the Van Allen Belt radiation to measure the energy flux and radiation intensity, and finally the conclusion.

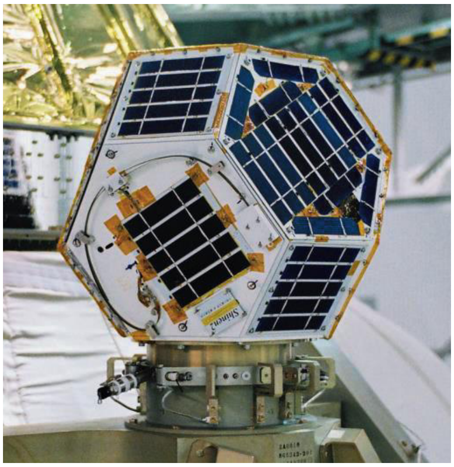

Fig. 1. Flight Model of Shinen2

2. Shinen2 Orbit Definition

Shinen2 probe doesn't possess a propulsion system, its trajectory is determined only by the impulse given by the rocket at the separation phase. The space probe doesn't have also an attitude determinate control system could be installed, can flies between periapsis 0.9AU to apoapsis 1.1AU. However, we should know the input parameters for Shinen2's orbit determination were given by JAXA [3], prior to launch day for estimating the trajectory of the space probe with earth orbit. The input data are described in Table 1.

Table 1. Input parameters for orbit of Shinen2

Parameters	Values	Unit
Time of separation (after launch)	6835	seconds
Distance from the center of Earth	9244.915	km
Latitude	0.034	degrees North
Longitude	189.94	degrees East
Inertial velocity	10357.221	m/s
Inertial velocity elevation angle	34.644	degrees
Inertial velocity azimuth angle	119.877	degrees
Japan time of launching	13:22:48	3-Dec-2014

The Fig. 2 defines 2 dimensional view of the distance between Shinen2 and Earth's orbit in time around the sun can be seen by using orbit method prediction simulated by Matlab software.

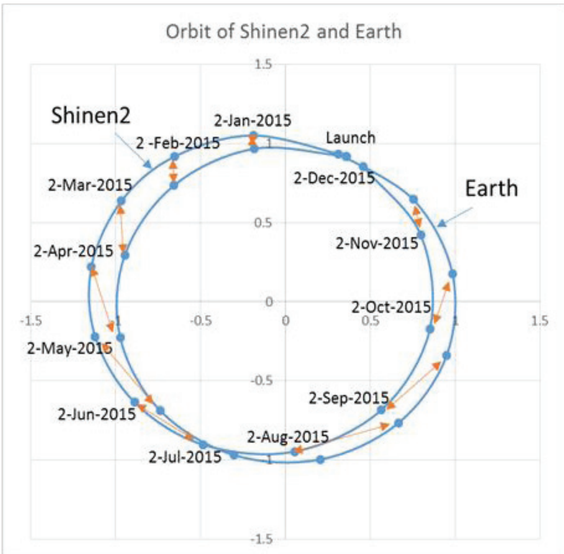

Fig. 2. Shinen2 and Earth's orbit

3. Shinen2 Structure

Shinen2 space probe designed as quasi-spherical shape to allow more uniform heat transfer compared with a cubic shape structure, the mass budget is 7.8 kg satellite with dimension 490×490×475 mm. The first space probe in the world to implement a Carbon Fiber Reinforced Thermo-Plastics (CFRTP) structure [4]. This material is widely used in the aerospace industry because of CFRTP`s wide range of specification strengths; high durability, welding possible, reduction of machining time. The Fig. 3 shows the internal structure made by Aluminum alloy Al6061-T6 and the external structure made of Polyetheretherketone PEEK/CFRP of Shinen2 [5].

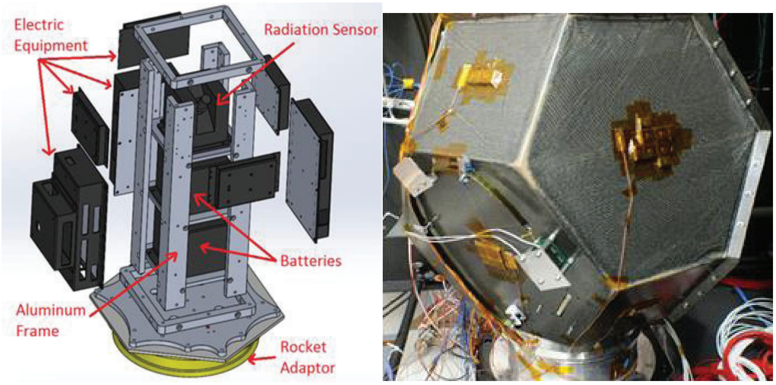

Fig. 3. Overview of the internal and external CFRTP structure of Shinen2

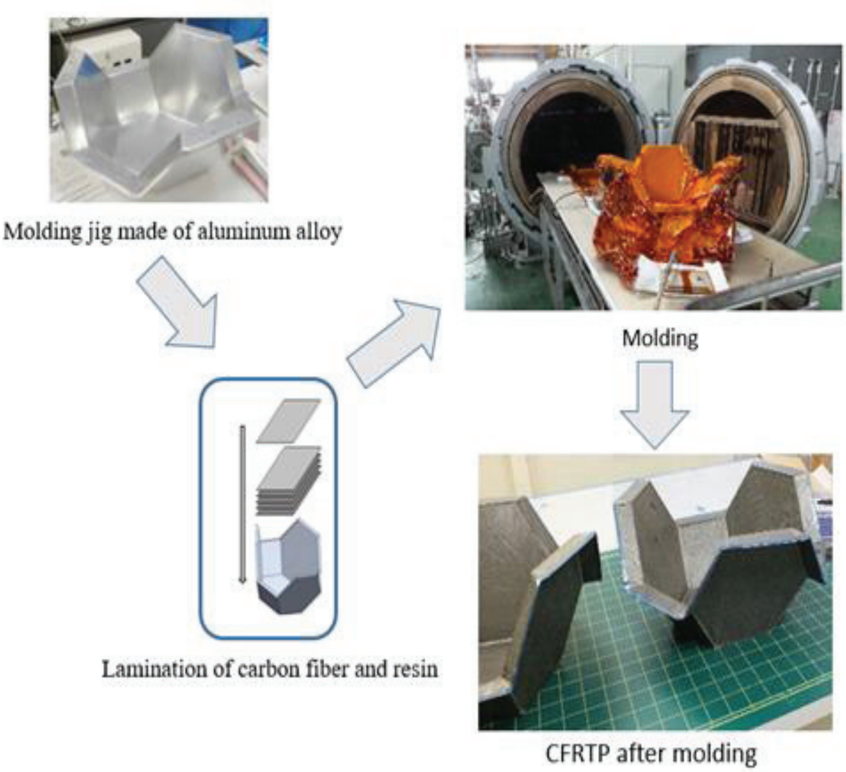

Fig. 4. PEEK/CFRP structure manufacturing process

4. Shinen2 System Control Unit SCU

The functional block diagram of Shinen2 (Fig. 5) describes the function of each lines (A, B, C) how are connected, more important the link approach control line between each line in red color, the black line shows the control power between the three power control unit PCU's of each line including UHF/VHF transmitter TX and receiver RX for tracking the information.

The SCU checks the active confirmation of all the Shinen2 units and Housekeeping data HK, describes some parameters such as battery temperature, flow currents and voltage on PCU. Moreover, SCU collects radiation sensor data from space. The function of communication control unit CCU transmits HK data and radiation data from the SCU. The CCU modulates the SCU data sent for transmitting to the ground station. The B-line for beacon signal was used as a battery for the C-line, but the other B-line system was independent. The A-line was independent from the other line systems. The Shinen2 has five antennas, two mono-pole antennas for down-link and a patch antenna was used for the B-line of the beacon signal.

The Shinen2 SCU is the main board that control all lines by using PIC controller 16F877A, designed for communication to deep space, to measure the cosmic radiation using sensor detector and control power distribution. The SCU have different goals as controlling the PCU, gathering the HK data (electric parameters, temperature, and radiation intensity) using amateur radio band. The Fig. 6 defines command generator using the PIC16F877A programmer with different input and output pins, each pin have function, for the input pins, RC 7 to transmit the data using UART interface, RC5 to receive data and VDD pin for generating power. The VCO is added as an electronic control oscillator as output block integrated in the scheme that contains some electric components (resistances, capacitor…) to control the power distribution, current and generate the analog signal, whose oscillation frequency is controlled by a voltage input. The applied input voltage determines the instantaneous oscillation frequency [6].

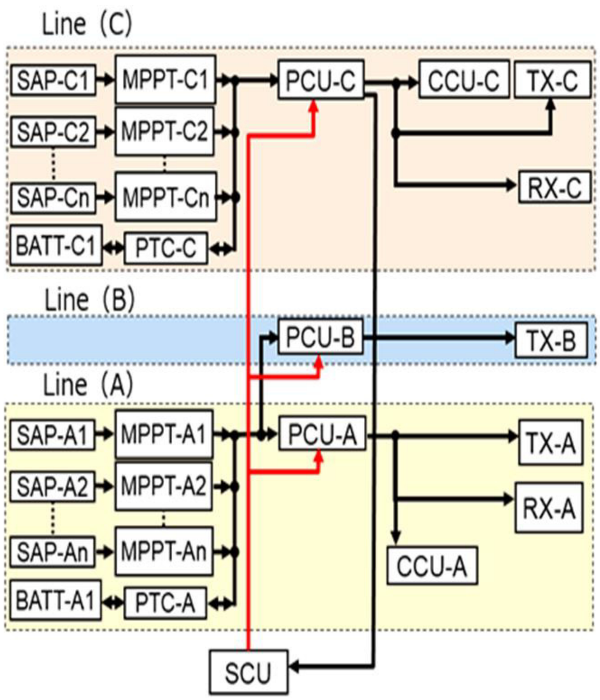

Fig. 5. Control block diagram

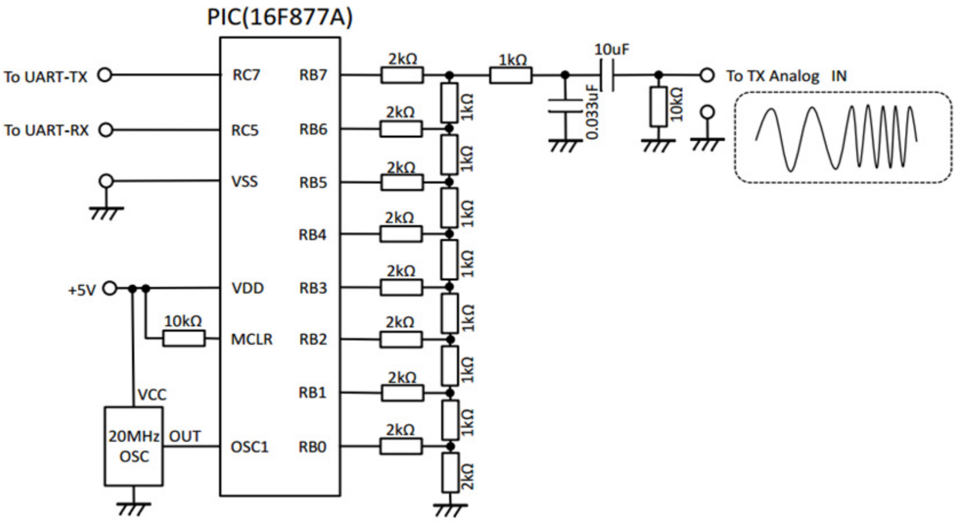

Fig. 6. Command generator and VCO of Shinen2

The Fig. 7 shows the concept of transmitting the commands after selecting the transmitter UHF band (437MHz). In the PIC programmer, we will create our frame data contain different bytes, coding part added in the block to correct Bit Error Rate BER, by applying oscillator control to generate the voltage and convert the digital bits (20 samples per second) to wave signal as audio. At the end, we should sent wave signal with frequency (437 MHz) to ground station using software Signal Defined Radio HDSDR [6].

4.1 Shinen2 Power Control Unit PCU

In this part, power unit of Shinen2 developed by student in Kyushu Institute of Technology and Kagoshima University which appearances the PCU electric board defined in Fig. 8. The internal structure of Shinen2 shown before, use one series of lithium ion battery (3.6V) works in range temperature vary from -20℃ to 50℃, contains 16 batteries in parallel, one used for redundancy and other series added for protection circuit, the average capacity is about 52 Ah. The Shinen2 have Solar Array Panel, type silicon cells with efficiency 17%, for A-line (11 arrays) and C-line (10 arrays), each cell can generate maximum power about 2.70W. In the system architecture, defined above, the SCU have also Maximum Power Point Tracking (MPPT) connected to Solar Array Panel (SAP), with efficiency 75%, input voltage vary from 0.5V to 5V works in range temperature from -30℃ to 150℃. The power consumption of each component defined in bus system described in Fig. 9 and the battery protect circuit performance shows in Fig. 10.

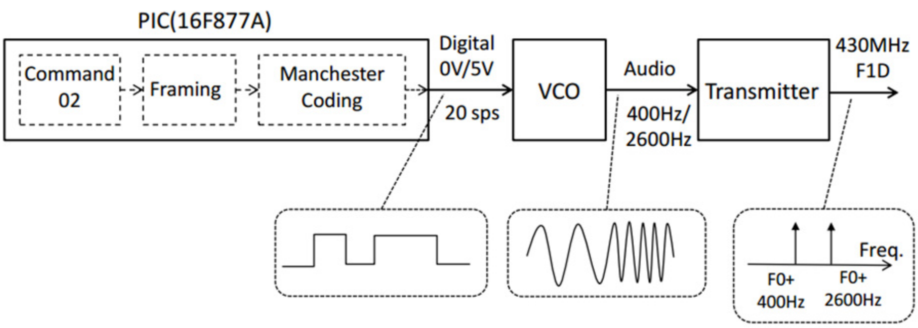

Fig. 7. Configuration of command transmitter

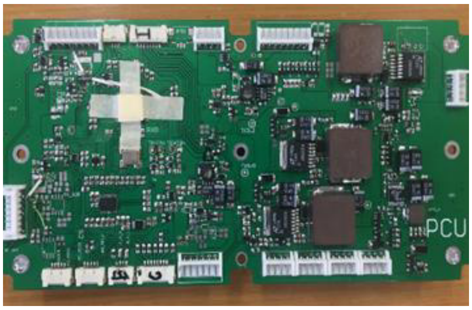

Fig. 8. PCU board model

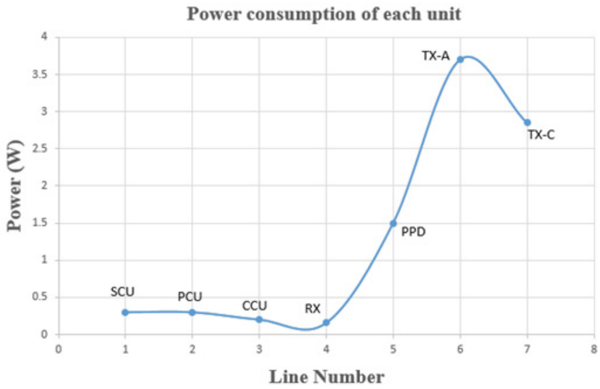

Fig. 9. Electric components consumption of Shinen2

4.2 Shinen2 Communication Control Unit CCU

The communication conceptual diagram of Shinen2 contains more links means lines of communication, both of them using the frequency amateur radio band as amateur radio service. The main specification of each system shows in the Table 2, by applied different techniques as interfaces used for developing our data as WSJT (Weak Signal& Joe Taylor) and Ax25 with require bit rate for the uplink and downlink, different mode of modulation adapted to the link design like binary phase shift keying BPSK [7], modulation without subcarrier F1D and modulation with subcarrier A1A…etc.

The Spacecraft operation system (C-Line) use the exchange of operational data of the spacecraft between the ground control station and the spacecraft. The radio relay line (A-Line Amateur Radio Relay Experiments) used for long-distance communication experiments with the ground of amateur radio. The B-Line beacon signal, used as a line for the spacecraft identification.

The diagram of communication system shows in Fig. 11 of the three communication lines of the Shinen2 probe including the channels (CH1 to CH5) specified in previous table in different ground stations at Kagoshima University, Kyushu Institute of Technology and Tohoku University.

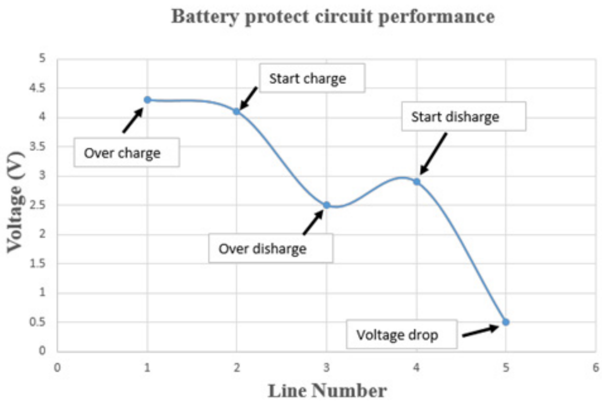

Fig. 10. Battery protect circuit performance

Table 2. Frequency and link design of Shinen2

System	Channel	Uplink/ Downlink	Frequency (MHz)	Transmit Power(W)	Modulation type	Interface	Bandwidth (KHz)
S/C - Operation	CH1	UP	145	50	F1D	Ax.25	16
	CH2	Down	437	0.8	F1D	WSJT	3
Relay- Satellite	CH3	UP	145	50	F1D, A1A	Ax.25	16
	CH4	Down	437	0.8	F1D, A1A	WSJT	16
S/C - Identification	CH4	Down	437	0.1	A1A	Morse	0.5

4.3 WSJT Communication System

One of the more important mission of Shinen2 is transmitting to deep space that means the transmitting signal is very weak. For this reason we applied the model interface called WSJT, the purpose to demonstrate new communication system using the amateur radio band by using the software HDSDR for receiving data [6]. It is useful as a weak signal communication program developed for communication facilities and low power facilities. The downlink of the C-line and the A-line communication system was adopted for the WSJT system. The WSJT system has a specific talent. The signal level used is 10 dB lower than the CW signal level, which used an acoustic signal of PC, and integrated the noise level below the signal. The Fig. 11 describe the WSJT system diagram. In the 200 Hz to 1.4 KHz of bandwidth, seven spectrum slots per 200 Hz steps are prepared, and the lowest frequency is always used for the output. The other spectrum slots were assigned and control characters, for example from 0 to 9 and BOF (Begin OF Frame). In order to achieve a constant transmission power and increase as much transmission power per slot as possible, a combination of the two spectrums was selected. The power per spectral line was 0.2 W (for all lines 0.8W). The number of spectrums is always three on the transmit signals described in Fig. 11. Error detection data analysis was always used [7].

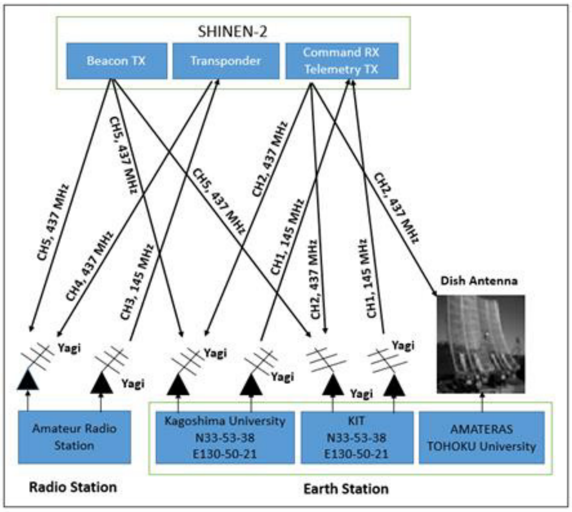

Fig. 11. Communication conceptual diagram

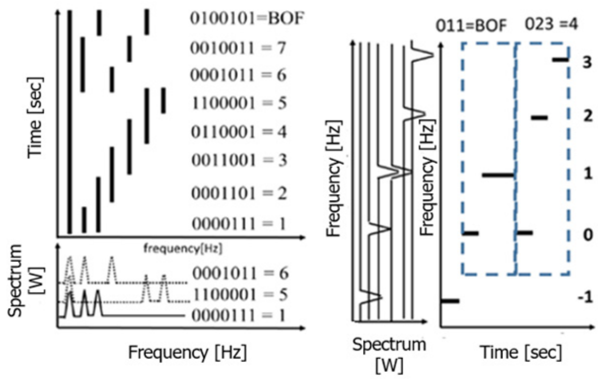

Fig. 12. WSJT system of Shinen2

On the right graph of Fig. 12, present the power spectrum by varying the frequency and the horizontal axis is the time. When there are three numbers, they are converted to the corresponding character. The assignment of the code to the eight characters. For example, when the ground station received the code “011”, it obtained the data of the beginning of frame BOF. In addition, when we received the code “023”, it obtained the data “4”. To analyse the received data of the Shinen2. The down-link data were composed of 13 bytes, with 2 bytes of synchronization by using the 2 bytes of CRC. Moreover, the bit rate of the WSJT is 1 bps, and the down-link data were needed to receive 2 minutes per frame data. In addition, Shinen2 sent the same data two times, because the received data improved the construction.

5. Payload of Shinen2

The payload of space probe was installed for measuring radiation intensity using particle pixel detector PPD to evaluate the distribution of the cosmic radiation described in Fig. 13. The PPD was designed by NASA Johnson Space Center and Prairie View A&M University with low weight about 800 grams, operating capability for low power is near to 1 Watt, suitable for a period 2 to 5 years, ability to generate data for low bit rate transmission 9.6Kbps with a good tolerance in deep space environment [8].

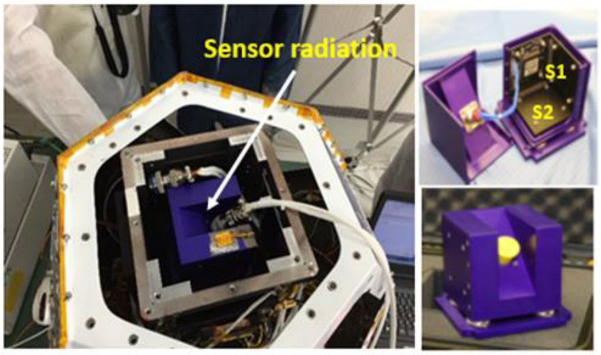

Fig. 13. Prototype radiation sensor of Shinen2

This section describes sensor testing procedure of the PPD (S1,S2) for the measurement of cosmic radiation in deep space, However, to verify the operational capability of the developed units [9], some radiations sources such Cobalt (Co-60), used for testing the payload with low energy radiation. Before connecting the cable to power supply, the voltage should be 5V (Volts) and max current is set to 500mA. After connecting the cables to RS422 USB converter, and to the power supply. The voltmeter should read 5V and current meter is about 279mA (mili Amperes) described in Fig. 14. The software Matlab used to call the function (sensor1-lowflux-energy1) that contain the code for plotting the radiation hits of S1 shows in Fig. 16. When we connect the USB cable to the laptop. Yellow LED will be lit on the RS422 converter indicating is connected and ready to use for communication. After running the program we should enter the number of frame generated (example: 1080000 frames) defined in Fig. 15. Furthermore, the program will start collecting date and a window will display number of frame and number of counts after 1 hour that means the green LED blinking very fast indicating data exchange. The same procedure for the second sensor by calling the second function in Matlab (sensor2-lowflux-energy2). Finally, the windows displays the number of hits of each sensor means that our sensor worked well , ready for orientation and installing in Engineering Model EM of Shinen2.

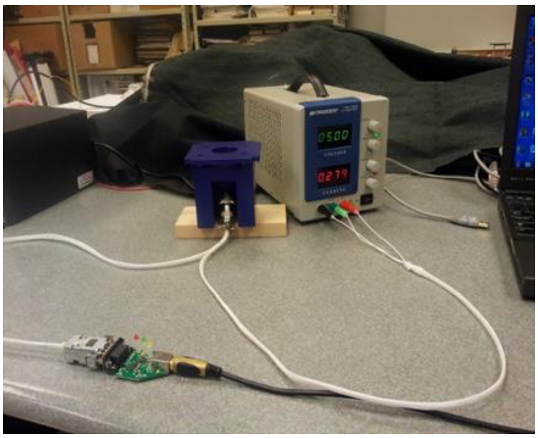

Fig. 14. Connecting the sensor to power supply and RS422 converter

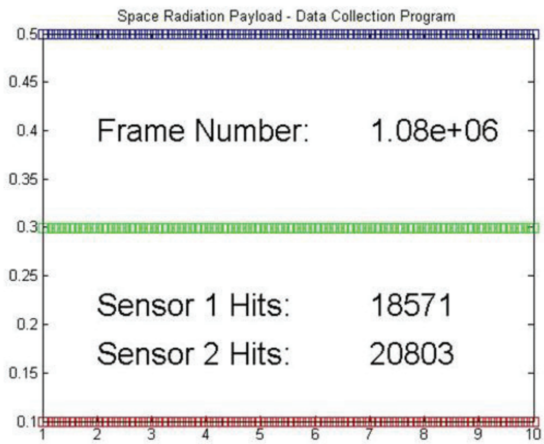

Fig. 15. Co-60 Frame data of space radiation payload

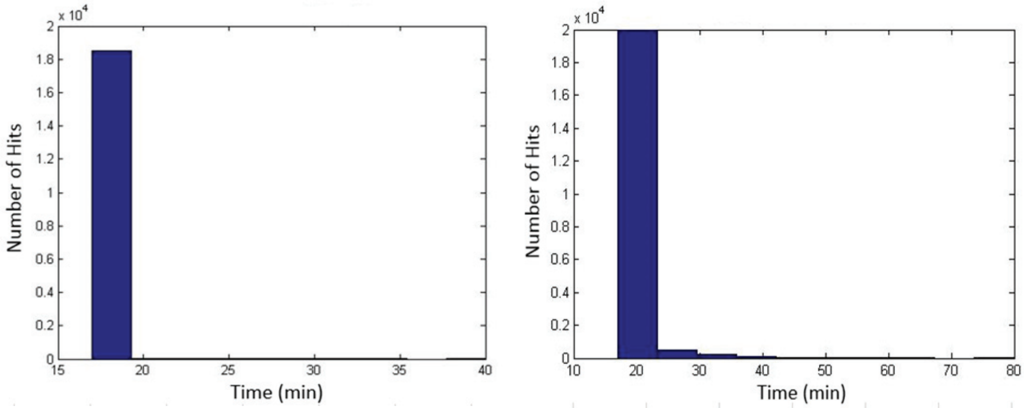

Fig. 16. (a) Radiation hits histogram of S1; (b) Radiation hits histogram of S2

5.1 Frame data

This section defines the type of frame data of Shinen2 from SCU to CCU data format shown in previous functional block diagram with red line for the communication link. Fig. 17 shows the frame data.

Fig. 17. Frame data of Shinen2

- 01frame = 16 Bytes (128 bits)
- Control code: 06 Bytes with variable length
- Data (CCU command)
- Data length (the length of the data source)
- Data: 8 Bytes
- Exit code2: Bytes

From this principal, we can define the telemetry frame data of our sensor PPD, to know each sensor how much has number of bytes before collecting all data from the signal wave saved in the software HDSDR, Fig. 18 defines the telemetry data of space probe Shinen2.

8 bits	8 bits	8 bits
Frame Sync	Sensor 1 Data	Sensor 2 Data

Fig. 18. Telemetry data of Shinen2

- 24 Bit Frame including 8 Bit Frame Synchronisation
- Byte 2: Frame Sync – 10101100 (0xAC)
- Byte 1: Sensor 1 pixel value (0x00 to 0xFF)
- Byte 0: Sensor 2 pixel value (0x00 to 0xFF)

6. Results and Discussion

Before launch by H-2A rocket, a vibration test of the flight model FM of Shinen2 was carried out by using the facilities at the Kyushu Institute of Technology. The Fig. 19 shows the outline of the vibration examination. These test results confirmed that the space probe had a certain resistant for every vibration of the H-2A rocket. Furthermore, the measured natural frequency of the Shinen2 was 350Hz; an exact agreement with the predicted value 360Hz using the simple analysis**.** The Shinen2 was safely deployed into deep space orbit by the H-2A rocket, and was beyond the lunar orbit in only 20 hours.

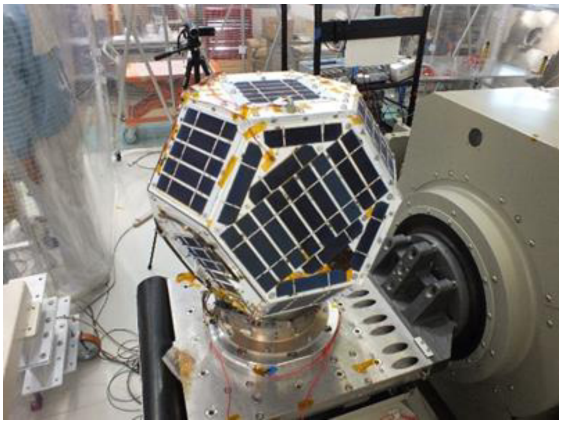

Fig. 19. The vibration test of flight model of Shinen2

Several ham radio operators around the world succeeded in receiving the signals transmitted by the UHF band on board the space probe Shinen2 using HDSDR Software Defined Radio [10]. The persons of representative ham operators are JR8LWY, JH6VAX, SQ5KTM and PE1ITR. When the Shinen2 flied around the lunar orbit, the received predicted temperatures of the surface structure, battery, transmitter and PPD sensor were 297K, 300K, 320K and 301K respectively. These are in good agreement with the measured data; 293K, 296K, 307K and 295K. This part describes the result of the received data from the Shinen2 defined in Fig. 20, and the Shinen2 checks if the SCU with payload PPD worked in deep space by the received HK data [11].

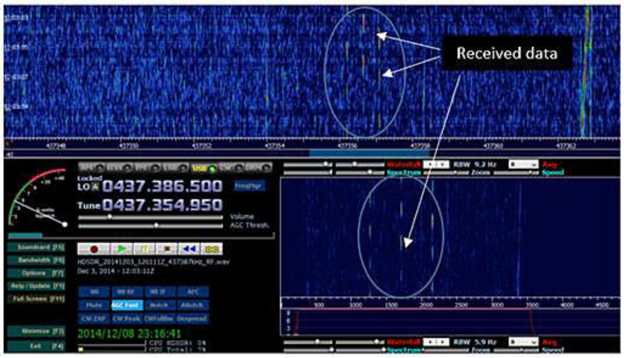

Fig. 20. The received data of Shinen2

The Shinen2 received the last data at 2.3 million km for approximately six days. However, only three days' worth of data could be analysed. It was difficult to examine all the data from the other days because of the week signal. Several data from the sensor should decrypted (acquisition data) after examined all frame data of the communication system. Hence, we are able to plot a histogram distribution of the cosmic radiation payload in an actual context with real data received from the probe, the measured cosmic radiation data from the S1 and the S2 sensors are shown in Fig. 21(a) caused by solar flares. We could see also that our sensor work normally in deep space, can measure the radiation intensity and after, the PPD of Shinen2 was caused by inner and outer radiation Van Belt shown in Fig. 21(b).

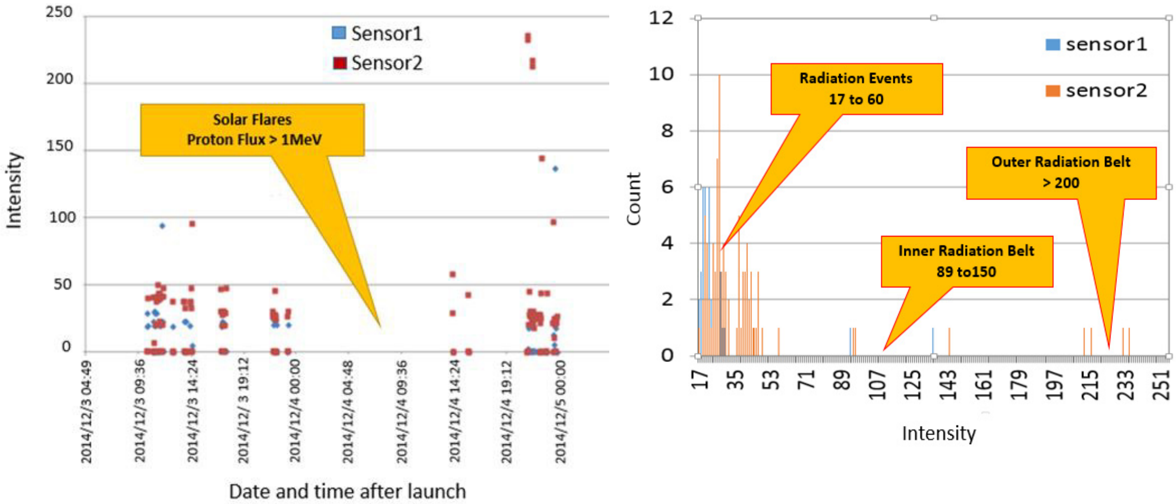

Fig. 21. (a) Histogram distribution of the first data set from Shinen2; (b) Radiation Intensity of Shinen2

7. Conclusion

In this paper a control system design for a deep space mission, Shinen2, was presented. This report presented a model of small probe deep space as Nano satellite describing each subsystems and defining main mission using the payload sensor in Kyushu Institute of Technology developed by the NASA-JSC with high performances to detect the measurement of cosmic radiation, it can survive in a strong radiation region such as the Van Allen belt radiation. Shinen2, could receive the house keeping HK data and radiation sensor data after launch. In addition, the data was normal while in deep space, therefore, the sensor of Shinen2 worked normal and can used for any application in deep space. For the future work will include new devices or units such the engineering unit detector used before but with high performance, different requirements and it can be used for long life cycle and with new design communication system.

Acknowledgements

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